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For IRAM use

Registration N°:

Date:

PROPOSAL FOR INTERFEROMETER

Deadline: 04 Mar 2004 Period: 15 May 2004 — 15 Nov 2004

TITLE

CO identification of (sub)millimeter galaxies IV.

CATEGORY: 1.3mm: ○ 3mm: ○ dual freq.: ● time filler: ○ special: ○

Scientific type: - Extragalactic: continuum ○ CO lines ● other ○

- Galactic: continuum ○ lines ○ circumstel. env. ○ young stel. obj. ○ cloud struct. ○ chem. ○ other ○

Observing type: mapping ○ detection ● size measure ○ snapshot ○ mosaic ○ other ○

ABSTRACT

We propose to continue our successful long-term program to determine, via CO rotational line emission, the dynamical/molecular gas properties of a sample of ∼ 30 SCUBA submillimeter and MAMBO mm galaxies. We have detected CO emission from half the sources observed so far, and propose to extend our sample by another 8 objects this summer. The preliminary results of our program already provide a huge leap in our knowledge of the gas masses and dynamical properties of the luminous, obscured galaxies that produce at least half of the energy emitted in the early Universe. It enables statistically meaningful comparisons with other populations and galaxy formation models, explores the feasibility of millimeter-based spectroscopic redshift measurements with current and future instrumentation, proves the reliability of radio identifications, serves as a database for calibrating present and future photometric redshifts, and provides a crucial test of galaxy formation models.

Is this a resubmission of a previous proposal ? no ● yes ○ – proposal number(s): .....

Is this a continuation of (a) previous proposal(s) ? no ○ yes ● – proposal number(s): N061,N028,M05D,MD-7

LST range(s) per configuration from: 6h to: 16h number of intervals: 12

from: 12h to: 20h number of intervals: 12

Configurations: **B** ○ **C** ● **D** ● **Any** ○ **30M** zero spacing ○

Frequencies (exact) 3mm: see attachment 1.3mm:

Confidential information:

List of Objects (give most common names) with equatorial coordinates in J2000 (accurate to 2″) and LSR velocities

Source	α_{J2000}	δ_{J2000}	V_{LSR}
SMMJ030244	03 02 44.56	+00 06 32.3	z=2.4345
SMMJ030227	03 02 27.73	+00 06 53.5	z=2.2574
SMMJ123549	12 35 49.44	+62 15 36.8	z=2.2032
SMMJ123555	12 35 55.14	+62 09 01.7	z=1.865
SMMJ123622	12 36 22.65	+62 16 29.7	z=2.4662
SMMJ123707	12 37 07.21	+62 14 08.1	z=2.486
SMMJ131232	13 12 32.31	+42 39 49.5	z=2.3204
SMMJ221733	22 17 33.79	+00 14 02.1	z=2.5553

(continue on next page, if needed)

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who will reduce data: Neri et al.

join to this form: scientific aims ≤ 2 typed pages and ≤ 2 pages Figs., Tables and list of related publications

IRAM Plateau de Bure Interferometer: Proposal Technical Summary
Please fill one sheet per frequency setup

- **Program Title:**

CO identification of (sub)millimeter galaxies IV.

- **Source position and velocity:**

Source	RA (J2000.0)	DEC (J2000.0)	LSR Velocity (km/s)
SMMJ123549	12 35 49.44	+62 15 36.8	z=2.2031

- **Category and Project type:** dual-frequency lines detection
- **Size of largest structure in (arcseconds)** unresolved
- **Expected continuum flux:** 1–4 mJy at 1.3mm
- **Expected continuum source size:** unresolved
- **For pure continuum projects:**
  - *Preferred observing frequency:*
  - *Expected Line contamination at observing frequency:*
  - *Frequencies to avoid:*
- **For line projects:**
  - *Receiver configuration (fill in empty columns) :*

	line name	Freq. (GHz)	band	
LINE	12CO(3-2)	86-113	USB	/RECEIVER 1
LINE	12CO(6-5)	212-237	LSB	/RECEIVER 2

  - *Correlator configuration (fill in empty columns) :*

	width	freq.		Receiver		Mode
SPECTRAL 1	160	180	/RECEIVER	1	/BAND	SSB
SPECTRAL 2	160	320	/RECEIVER	1	/BAND	SSB
SPECTRAL 3	160	460	/RECEIVER	1	/BAND	SSB
SPECTRAL 4	160	600	/RECEIVER	1	/BAND	SSB
SPECTRAL 5	160	180	/RECEIVER	2	/BAND	DSB
SPECTRAL 6	160	320	/RECEIVER	2	/BAND	DSB
SPECTRAL 7	160	460	/RECEIVER	2	/BAND	DSB
SPECTRAL 8	160	600	/RECEIVER	2	/BAND	DSB

  - *Expected width of spectral line (to zero power) and narrowest feature:* $\sim$ 400 km/s
  - *Number of lines observed simultaneously (add sketch of frequency setup):* 1–2 (varies by source)
  - *Line frequencies:* varies by source
  - *Expected source size in each line:* unresolved
  - *Expected line strength:* 0.5–6 mJy
- **For mapping projects:**
  - *Configuration required (BC, CD, D, other):* D
- **For detection projects:**
  - *Observing time required:* 20 hours for each object
- **For snapshot or size measurements:**
  - *Baseline range in meters:*
  - *Configuration list:* C,D
  - *Number of hour angles per baseline:*
  - *Observing time per hour angle:*
- **Phase Calibrators (2 or more):** varies by source
- **Amplitude Calibrator:** 3C345
- **Required accuracy of bandpass calibration:** good
- **Special requirements:** none

CO identification of (sub)millimeter galaxies IV.[1]

Proposal history: Considering the fundamental importance of the dusty far-IR/submm population for the understanding of galaxy formation and evolution, recognizing the difficulties of reliable spectroscopic identifications of faint submillimeter (submm) galaxies, and realizing the strategic importance of such work for IRAM and for the scientific preparation of large future international programs such as Herschel and ALMA, in July 2002 we proposed to the IRAM Director CO detection observations on a new sample of distant submm sources with recently established spectroscopic redshifts. The program was started in the late summer 2002 semester with three targets. Our subsequent regular proposal M05D was accepted for the winter semester, with the option for a long-term status (> 4 semester, > 30 sources) if the program proves successful, and if a progress report is submitted each semester. Such a report was submitted each semester since, with a list of new targets, a total of 22 so far. Our program has so far been very successful in that of which 14 sources observed to date, CO was detected in 7 (Fig.1). For three of the detected sources we recently obtained high resolution observations for which good quality data have just been taken, improving the resolution of the CO maps to better than 2 arcsec (data in the process of being analyzed). Below we give a brief update on the main program status. For new PC members we repeat the science motivation. The results of our observations are reported in an ApJ Letter (Neri et al. 2003), in a conference contribution (Genzel et al. 2004), and in more detail in a paper in preparation by T. Greve as part of his PhD thesis. Given the volume of our request, we have extended the length of the proposal beyond that recommended, hoping that the PC will permit this exception.

Background

At least half of the cosmic extragalactic energy density (not counting the cosmic microwave background) emerges at far-infrared wavelengths (Fixsen et al. 1998; Hauser et al. 1998). During the last years, surveys with SCUBA at $850\,\mu$m and MAMBO at $1200\,\mu$m have resolved a significant fraction of this background into a population of faint (mJy) submm sources that may be luminous and ultra-luminous infrared galaxies at redshifts $1 < z < 5$ (Smail et al. 1997; Hughes et al. 1998; Barger et al. 1998; Bertoldi et al. 2000; Dannerbauer et al. 2002). This population of luminous, dusty starburst galaxies contributes significantly to the cosmic star formation at high redshift and may trace the epoch of bulge/elliptical formation. While surveys at submillimeter and millimeter wavelengths have by now identified several hundred sources, spectroscopic redshift and CO detections had, until the summer of 2002, only been obtained for two sources at $z \sim 3$ (Ivison et al. 2001; Frayer et al. 1998; Genzel et al. 2003), mainly because of the faintness of their optical/near-IR counterparts and the lack of accurate positions.

Recently some of us have been able to substantially increase the number of accurate source positions from deep VLA radio maps (Ivison et al. 2002). Optical follow-up spectroscopy at Keck for these radio-detected submm sources was surprisingly successful, resulting in a reliable sample of now > 90 sources with optical redshifts (Chapman et al. 2003).

Based on these results, we have observed 14 sources with the IRAM Plateau de Bure interferometer since the summer of 2002, detecting CO emission lines in 7 of them, confirming in a robust way the optically determined redshifts. Eight additional targets are scheduled in the current winter semester. These observations have demonstrated that the strategy adopted for our proposed long-term program is successful. Detecting CO line emission in ca. 30 SCUBA and MAMBO sources for which both accurate positions and optically-determined redshifts are now available, will enable us to confirm that the (sub)mm population indeed has a mean redshift of $z > 2.5$ and contributes about half of the high-z star formation activity. It will also provide the first sample of high redshift luminous infrared galaxies for which detailed studies of the intrinsic source properties are possible, which eventually allows size and mass estimates of these objects that provide a unique test of galaxy formation models (Fig.4).

Scientific goals

The scientific goals of this long-term program are to:

- Detect CO rotational line emission with moderate resolution (D-configuration) interferometric observations for a significant and representative sample of 20 or more galaxies, increasing the prior number

[1] This program is part of the PhD thesis of Thomas Greve, to be filed in the Fall 2004, supervised by R. Ivison.

of CO-confirmed redshifts by a factor of 10, at which point statistically meaningful comparisons to other populations and galaxy formation models can be made.

- This sample size will also be sufficient to determine the mean gas and dynamical mass, and velocity width for two redshifts bins, thus beginning to study the evolution of gas and mass properties of the most massive star-forming (proto-elliptical) galaxies in the history of the Universe.

- Explore the intrinsic source properties (gas mass and physical properties, dynamical mass, source size, relationship to emission at other wavelengths) by more detailed and spatially resolved 1–3 mm PdB interferometry of a sub-sample of the program sources. As has already been shown in two cases from our program (SMM J04431 and SMM J16368), such spatially resolved images deliver critical information in testing current hierarchical galaxy formation models (Fig.4), exploring how early and with what mass the luminous far-IR/submm galaxies were formed. We may also be able to constrain the CO-luminosity function of bright sources at high redshifts (as Keres et al. (2003) did for a local sample), and thereby study its evolution, and constrain the total mass density of cold neutral gas in the early Universe.

- survey the local environment of SMM sources for companions, and for other CO or continuum sources, in order to clarify the importance of merging.

- Explore the molecular gas properties of galaxies with strong and weak/absent AGN.

- Test the reliability and multiplicity of radio and optical identifications of (sub)mm galaxies, e.g., look for situations where the CO (and submm) source is related to the optical/NIR or radio ID – but is actually physically distinct.

- create a database for calibrating present and future photometric redshifts, which are degenerate in redshift and dust temperature.

- Explore the general feasibility of millimeter-based spectroscopic redshifts with current instrumentation. In addition, the detection of CO will open the door for observations of other CO transitions and of other molecular and atomic species (e.g. HCN and CI), which will allow to study the properties of the ISM in detail in a large sample of high$-z$ sources. Our CO survey has thereby the potential to act as a spearhead project for ALMA, and may well present a major legacy of IRAM.

Observations to date

By now we have observed 14 sources (Table 2), selected on the basis of strong (sub)mm emission, clear radio identifications, and the most reliable redshifts available at the time of observation. CO line emission was detected towards 7 sources (Fig.1). Eight more objects are scheduled to be observed in the current semester. The reason for the non-detection of half of our sample may either be a lower CO-to-FIR luminosity ratio for those sources, or yet too inaccurate redshifts. Our new Hα Keck/LRIS redshifts may improve latter significantly. Our CO detections show a wide variation in source properties. In at least one case, the targeted object is not the CO and continuum source. The line profiles show a range of shapes and widths (median 600 km/s), and for two sources a double horn structure characteristic of rotating disks. Some of the shapes are indicative of dynamically perturbed or interacting systems. In several cases the source appears resolved, which motivated higher resolution follow-up studies in three object (Our Bure W03/04 program, Neri et al.). The CO detections toward SCUBA submm sources

- provide an important confirmation of the optical/UV redshifts. It is interesting that their redshift range is close to the peak of the merging assembly history of galaxy formation. The formation of such massive systems at $z \sim 3$ is not easy to understand in current hierarchical models of galaxy formation (e.g., Genzel et al. 2003). If all SMM galaxies were similar to those we observed, their abundance would be inconsistent with current semi-analytic models of cold dark matter galaxy formation (Fig.4).

- locate the actual submm source. In most cases, the identity was ambiguous before our observations. In one case, the optical redshift did not correspond to the submm/CO sources, indicating a strong clustering of galaxies in their proximity. The multiple nature of the submm background sources may in fact explain why we were able to detect strong UV emission lines in these gas- and dust-rich sources.

- allow to derive the dynamical masses associated with these luminous infrared galaxies, supporting the interpretation that this population consists of gas-rich and massive ($\sim 10^{11} M_{\odot}$) interacting starburst/AGN systems, of very massive galaxies with deep central potential wells. The median velocity FWHM of our sample is 600 km/s, indicating that these galaxies have over 12 times the mass of a typical Lyman-break-galaxy at $z \sim 3$.

A detailed analysis was completed for the first three targets we observed (Neri et al. 2003). The current analysis of a larger sample will be part of the PhD thesis of T. Greve.

Future prospects

Based on these initial observations, it is clear that our program is demanding in observing time even with the superior sensitivity (a factor 5 relative to OVRO) of the PdBI, requiring 2–3 tracks per source for an initial detection, and more for follow-up at higher resolution. We had anticipated that this cooperative program would require at least 2 years for execution. With this report we restate our request for a long-term allocation to determine the CO properties of a sample of ~ 30 SCUBA submm galaxies, continuing this summer with another 7 new objects – plus one for which we have recently obtained a more accurate Hα redshift that is 1500 km/s off the prior Lyα redshift, which did not produce a CO detection. This will bring the total number of objects observed to 29, of which we hope to detect –especially with the new Hα redshifts– at least half. This approaches our set goal to observe a significant number of sources (>30) in order to be able to look for any redshift evolution in the FIR to CO luminosity, masses, and also to discern any differences between objects with and without AGN.

Using multi-object spectrographs at the Keck and Gemini telescopes our program to determine optical redshift for both millimeter (MAMBO) and submillimeter (SCUBA) selected galaxies continues now targeting mainly MAMBO sources. A very recent Keck LRIS observation run has yielded a number of additional excellent targets for PdBI observations, and additional NIRSPEC/Keck (3 nights) and OHS/Subaru (3 nights) runs in early April may add to this set. Some of the newest sources, if they show more reliably redshift estimates, we might request to substitute for the sources in our current list. The new near-IR spectra showing Hα (Fig.2), which should more accurately trace the redshift of the ISM in the galaxy as it arises from a greater fraction of the gas, being less prone to emission in highly-excited, fast-moving outflows offset from the redshift of the neutral ISM.

Observing strategy

For the coming summer semester we propose to observe $\sim$ 8 objects for which optical redshifts were obtained with an accuracy of $\Delta z < 0.005$ (see attached source list). We concentrate on detecting the 3 mm CO line emission, but will use the 1 mm receivers to try determine accurate continuum positions and fluxes, to estimate source sizes and to observe an additional CO tracer.

Assuming parameters from Version 3.7-00 of the Bure manual and our previous experience, with 5 antennas and summer conditions we expect that a single transit (giving eight hours on-source) will yield 1σ sensitivities of 0.8 mJy per $\sim 100\,\mathrm{km\,s^{-1}}$ channel at 3 mm, and 0.8 mJy across the 1 mm continuum bandpass (averaging both sidebands). Requiring a $\geq 5\sigma$ detection and a cross-check of having at least two $\geq 3\sigma$ detections in independent datasets, we will need 2–3 tracks per source, or a total of 16–24 tracks for eight sources. We request on average 2.5 tracks per source, and thus **a total of 20 tracks**.

To correct for the likely systematic blueshift of UV line features relative to CO emission, we will tune the 3 mm receivers slightly redward of the measured UV redshifts, except in cases where we have spectroscopic redshifts for nebular lines such as Lyman α. For the redshift uncertainty of $\Delta z = 0.005$, any source at $z \geq 1$ should then have the CO line peak fall within $0.5 \times 580\,\mathrm{MHz} = 290\,\mathrm{MHz}$ of the 3 mm band center.

The present proposal requests observing time mostly for the D configuration, which is well suited for detection experiments. Wemay consider observing the second or third track inthe C configuration if the source is well detected in D.Such higher resolution datayields crucial information on the source size.

Because of our ongoing analysis of recent spectroscopic near-IR Keck data, we propose to retain the possibility of exchanging targets in the source list for better targets we might identify, and in particular for sources from the MAMBO deep fields. In each such case a written request for changing the source will be submitted to the IRAM director. A 'better' target would be one with a clearer optical/IR identification, a stronger (sub)mm flux, or a more accurate redshift.

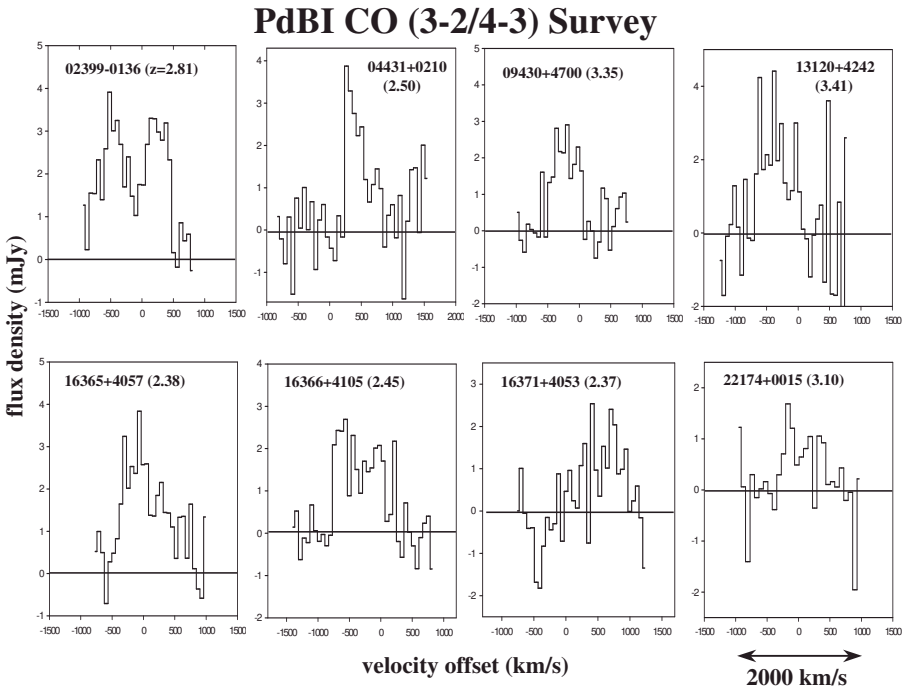

Figure 1. CO(3-2) and (4-3) spectra of the 7 submm galaxies which were detected in CO line emission, from a total of 14 surveyed to date. The spectrum of SMM J02399-0136 (from Genzel et al. 2003) is shown for comparison. The redshifts determined from the CO emission are given for each source.

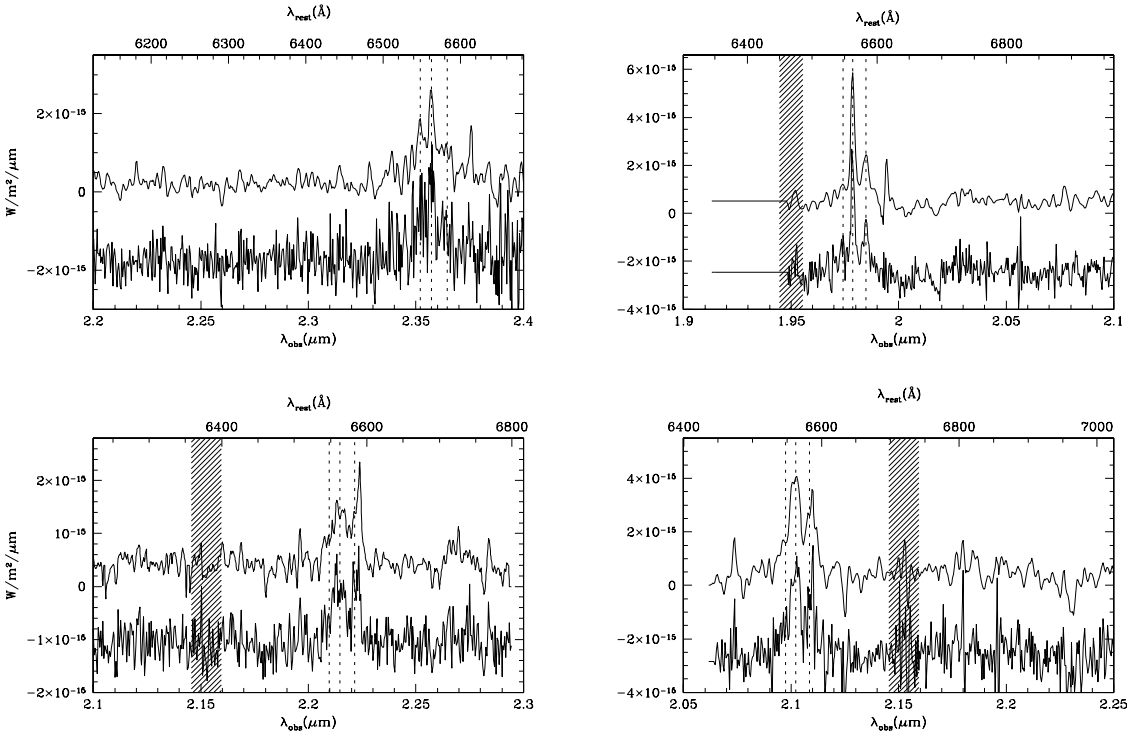

Figure 2. Examples of near-infrared spectra of four of the submm galaxies taken with NIRSPEC on Keck. Hα provides significantly more reliable estimates of the probable redshifts for the CO emission. These spectra also provide estimates of the star formation rates in these galaxies and the likely contribution from AGN to their emission (from the ratio of Hα/[NII]). The lower trace in each panel is the raw spectrum, the upper trace has been smoothed to the instrumental resolution. The vertical dotted lines show the wavelengths of the Hα and [NII] emission lines at the best-fit redshift and the shaded region denotes sections of the spectra which are badly effected by atmospheric absorption or emission.

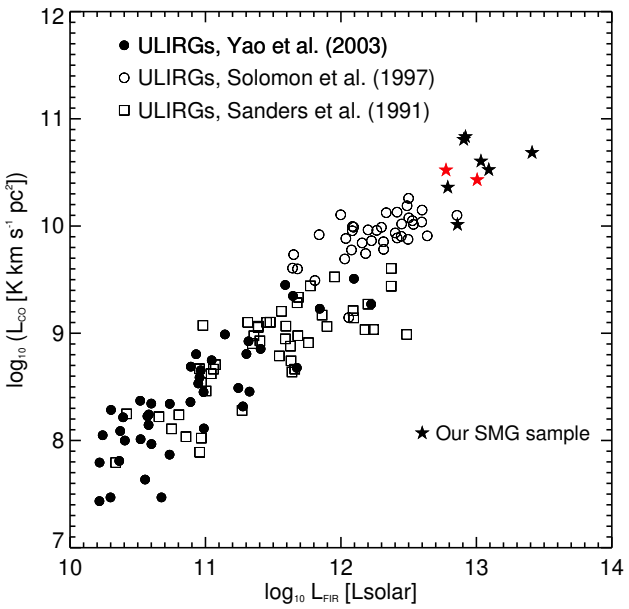

Figure 3. CO luminosity vs. far-IR luminosity for three samples of local (U)LIRGs (Sanders et al. 1991; Solomon et al. 1997; Yao et al. 2003) and for a sample of high-redshift (sub)millimetre selected galaxies (Neri et al. 2003; Greve et al. in prep.). The CO luminosities for the ULIRGs are all based on the CO $J = 1 - 0$ line, whereas for the sub-mm galaxies the line luminosities are derived from the $3 - 2$ (black symbols) and $4 - 3$ (red symbols) transitions. The far-IR luminosities were derived from IRAS 60/100μm fluxes which had been measured for all the ULIRGs, and in the case of the sub-mm galaxies were estimated using the FIR-radio correlation (Condon et al. 1992). For the submm galaxies the CO(1-0) luminosity was derived by assuming constant brightness temperature. (from Greve et al. in prep.).

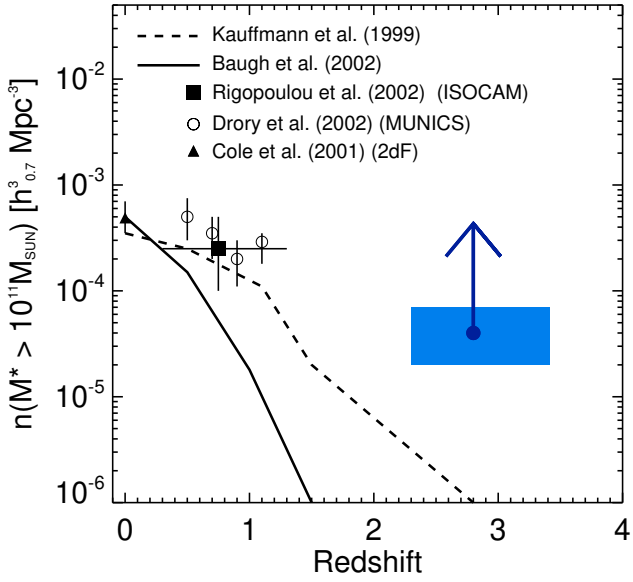

Figure 4. Comoving number density of galaxies with baryonic massess $> 10^{11} M_{\odot}$ as a function of redshift. The large rectangle shows the density of massive (sub)mm galaxies at $z = 2 - 3$, the arrow a likely factor 30 correction for burst lifetimes. Solid curves show the predictions of semi-analytic modelling – the two models use different values of Ω_b. The models strongly underestimate the observed number density of massive systems at high redshift. (Adapted from Genzel et al. 2004)

Table 1. Proposed targets.

Source	$S_{1.4}$ ±	S_{850} ±	z	tracer	Line	$\nu_{\rm obs}$
(1)	(2)	(3)	(4)	(5)	(6)	(7)
SMMJ030244.56+000632.3 (6)	51.0± 9.5	5.2± 1.1	2.4345	Hα	3-2	100.68
SMMJ030227.73+000653.5 (15)	217.1± 9.7	4.4± 1.3	2.2574	Hα	3-2	106.16
SMMJ123549.44+621536.8 (HDF.76)	74.6± 9.5	8.3± 2.5	2.2032	Hα	3-2	107.95
SMMJ123555.14+620901.7 (HDF.85)	212 ± 14	6.0± 1.8	1.865	Lyα	3-2	80.47
SMMJ123622.65+621629.7 (HDF.143)	70.9± 8.7	7.7± 1.3	2.4662	Hα	3-2	99.76
SMMJ123707.21+621408.1 (HDF.242)	45 ± 7.9	4.7± 1.5	2.486	Lyα	3-2	99.20
SMMJ131232.31+423949.5 (SA13.570)	94.8± 3.3	4.7± 1.1	2.3204	Hα	3-2	104.14
SMMJ221733.79+001402.1 (22.139)	44.5± 13.	7.4± 1.0	2.5553	Hα	3-2	97.26

Columns: (5) tracer of optical redshift; (6-9) CO transitions and frequencies to be observed at the PdBI.

Table 2. Status of the CO observations towards (sub)mm galaxies.

name	Pr	det	CO	S/N	pk	wid	I_CO	--offset--		z	S850	alias & comments
					mJy	kms	Jy*km/s	"	" km/s		mJy	
1	2	3	4	5	6	7	8 9	10	11 12	13	14	15
J044307.3+021023	MD-7	+	3-2			350	1.4 0.2	-1	-1 17	2.509	7.2	3as extended
J094303.7+470015	MB-7	+	4-3			420	1.1 0.1	-4	-1 -207	3.346	10.5	H6,wrong opt ID
J163650.4+405735	MA-7	+	3-2			840	2.3 0.2		115	2.3853	8.2	N2850.4
	M-14	+	7-6				1.1 0.2		-85	2.383		
J105155.5+572313	MB5d	-	4-3							(3.70)	4.5	LE850.18
J105230.7+572210	MC5d	-	3-2							2.6	11.0	LE850.6
J105238.3+572436	MD5d	-	3-2							3.0	10.9	LE850.2
J163631.5+405547	ME5d	-	3-2							2.28	6.3	N2850.13
J163639.0+405636	MF5d	-	3-2							2.04	9.0	N2850.7
J163658.2+410523	MH5d	+	3-2	7.8	1.8	700	1.3	0	0 -300	2.45	10.7	N2850.2 ERO
J123600.2+621047	NI28	-	3-2							1.999		
J131201.1+424208	NC28	+	4-3	9.1	2.2	500	1.1	1	1 -400	3.408	6.2	extended
J131232.3+423950	ND28	-	3-2							2.32	5.9	latest Ha z: 2.3257
J163706.5+405314	NJ28	+	3-2	3.7	1.2	brd		0	0 +400	2.378	12	MAMBO Elais(46)
J221736.0+001554	NG28	+	3-2	4.1	.94	500	0.5	2	4 -400	3.097	6.3	(135)
J123553.2+621337										2.098	8.8	(82)
J123555.1+620901										1.875	6.0	(85)
J123600.1+620253										2.710	6.9	(92)
J123606.8+621021										2.330	11.6	(105)
J123621.2+621708										1.988	7.8	(140)
J163627.9+405811										3.180	6.3	(e.43)
J163655.7+405910										2.607	2.8	(m.20)
J221737.3+001025										2.639	6.1	(851)

(1) SMM object name, i.e. coordinate
(2) IRAM target name
(3) + detected, - not detected
(4) CO transition
(5) signal to noise of line peak intensity
(6) peak line flux
(7) line FWHM, in km/s
(8)-(9) integrated line flux and uncertainty, sigma
(10)-(12) offset in position and velocity from optical target
(13) redshift of CO line, or optical z
(14) 350 GHz continuum flux density
(15) SMM source alt. name, comments

References: • Barger et al. 1999, ApJ, 518, L5 • Bertoldi et al. 2000, A&A, 360, 92 • Chapman et al. 2003, Nature, 422, 695 • Dannerbauer et al. 2002, ApJ, 573, 473 • Fixsen, D.J. et 1998, ApJ, 508, 123 • Frayer et al. 1998, ApJ, 506, L7 • Genzel et al. 2003, ApJ, 584, 633 • Genzel et al. 2004, Venice conference • Hauser, M.G. et al. 1998, ApJ, 508, 25 • Hughes et al. 1998, Nature, 394, 241 • Ivison et al. 2002, MNRAS, 337, 1 • Keres et al. 2003, ApJ, 582, 659 • Neri, Genzel, Ivison, Bertoldi, Blain, Chapman, Cox, Greve, Omont, Frayer 2003, ApJ 597, L113 • Sanders et al. 1991, ApJ, 370, 158. • Smail et al. 1997, ApJ, 490, L5 • Smail et al. 2002, MNRAS, 331, 495 • Solomon et al. 1997, ApJ, 478, 144. • Webb et al. 2003, ApJ, 582, 6 • Yao et al. 2003, ApJ, 588, 771.